A Hybrid Programming Model for Compressible Gas Dynamics using OpenCL

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Why are programming models important?

The growing variety of heterogeneous and multicore HPC computing architectures means that we need new tools and programming models if we are to sustain code portability.

Roadrunner
AMD + IBM Cell

NCSA Blue Waters
Power7 + Accelerator

Cray Heterogeneous
AMD + nVIDIA

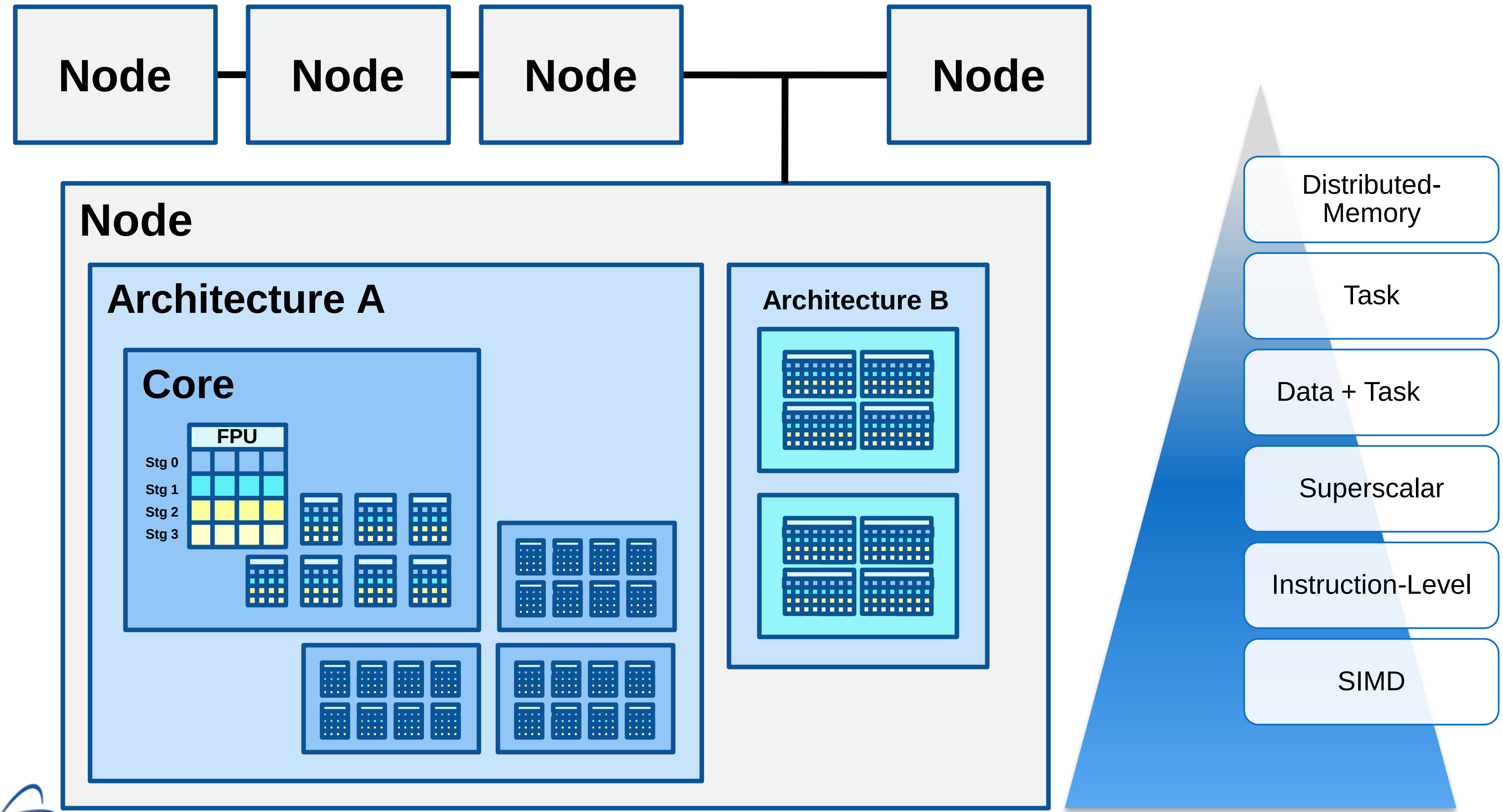
Sequoia
Blue Gene Q

Desktop
Multicore + Accelerator

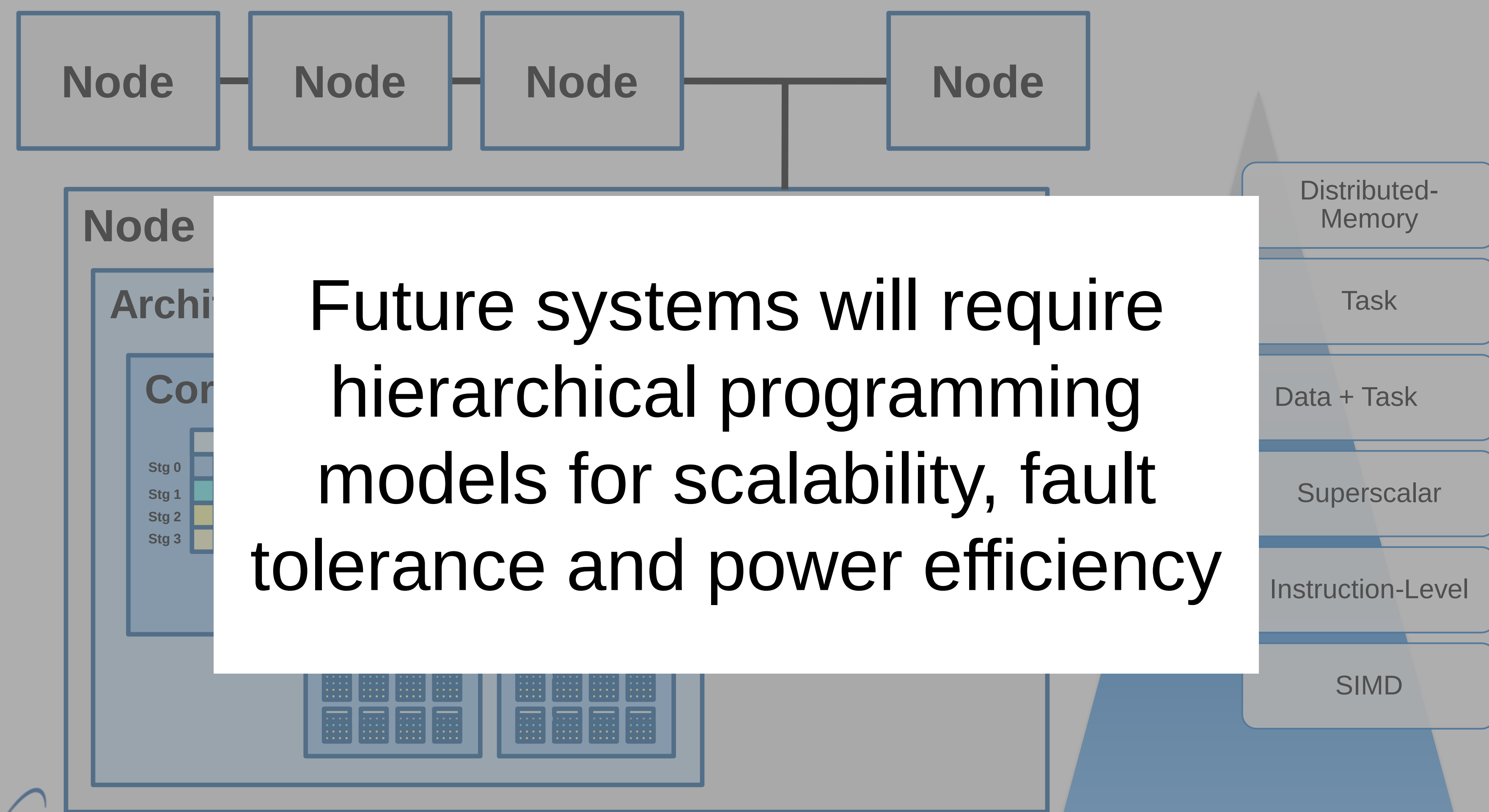
Some Challenges for Radiation Hydrodynamics on Modern Computing Architectures

- **Portability (#4)**
  - Current architectural diversity is challenging to support with single source base
  - Optimization strategies often depend on underlying architecture
- **Concurrency (#3)**
  - Hierarchy of parallelism: instruction-level, data, task, distributed-memory
  - Need expressions of radhydro algorithms to address all of them
  - Difficult to increase amount of data-parallelism
    - Affects scalability (think Opteron-only use of Roadrunner)
  - Task-level parallelism offers some promise
- **Fault Tolerance (#2)**
  - MTBF could be less than the time it takes to write a checkpoint
- **Data Motion (#1)**
  - Scalability will primarily be limited by power consumption
  - Data movement = Power

Hierarchy of Parallelism



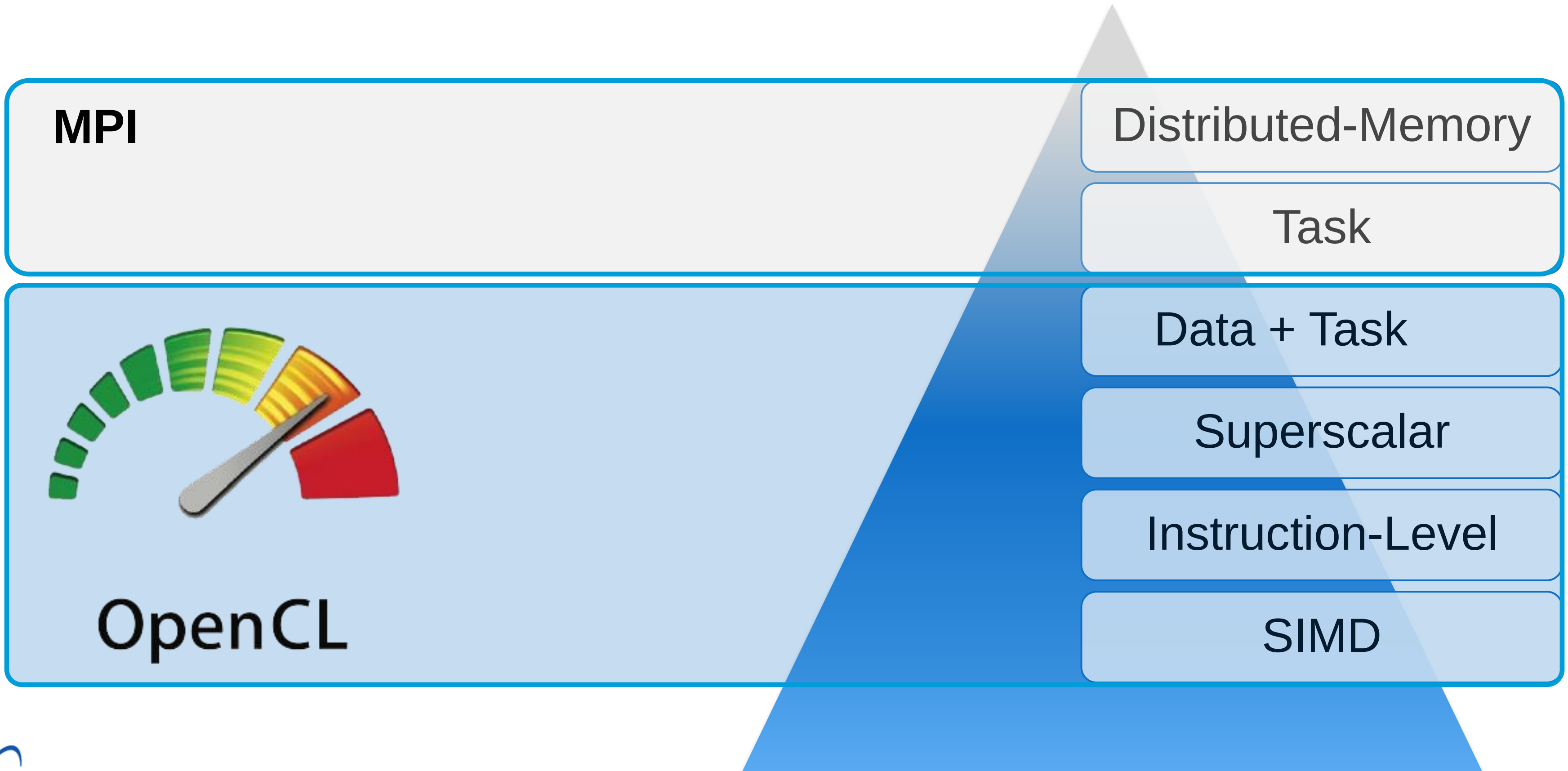
Hierarchy of Parallelism



Future systems will require hierarchical programming models for scalability, fault tolerance and power efficiency

One Possible Model

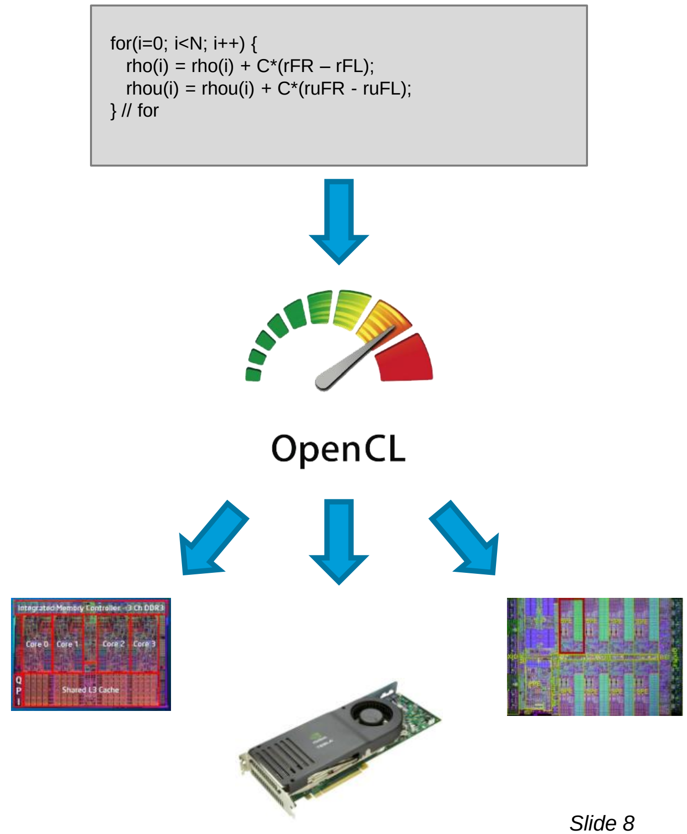
Use different tools for inter and intra-node control



What is OpenCL?

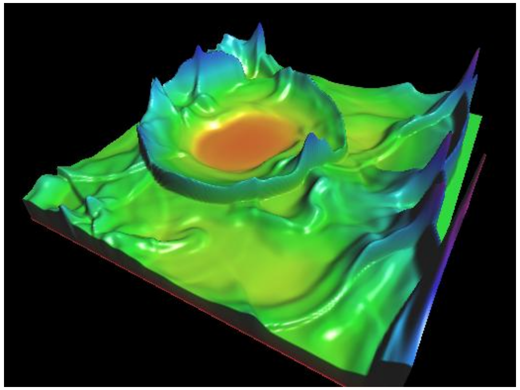
OpenCL is a framework for applications development on multicore, manycore and accelerated architectures

- **Runtime Environment**
  - Work distribution, dynamic kernel compilation
- **Application Programming Interface (API)**
  - Process launch, communication, synchronization
  - Topology interrogation (resource detection)
- **OpenCL C Kernel Language**
  - Low-level computational kernel language
  - Subset of C with extensions
  - Abstract vector types and intrinsics



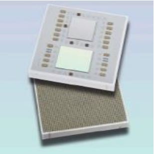
Proof-of-Concept Application

- **High-resolution direct Eulerian hydrodynamics solver**
  - MUSCL-Hancock Godunov method
  - Solves two-dimensional Euler equations
  - Structured grid with reflecting boundaries
  - Surface plot shows density on z-axis
- **Distributed-memory parallel with MPI**
- **Implemented with C++ and OpenCL**
  - Single-source implementation runs on all architectures
  - SC09 Demo ran on five different architectures using OpenCL compilers form three different vendors

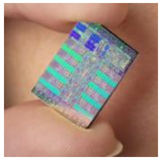


AMD Multicore

Intel Multicore



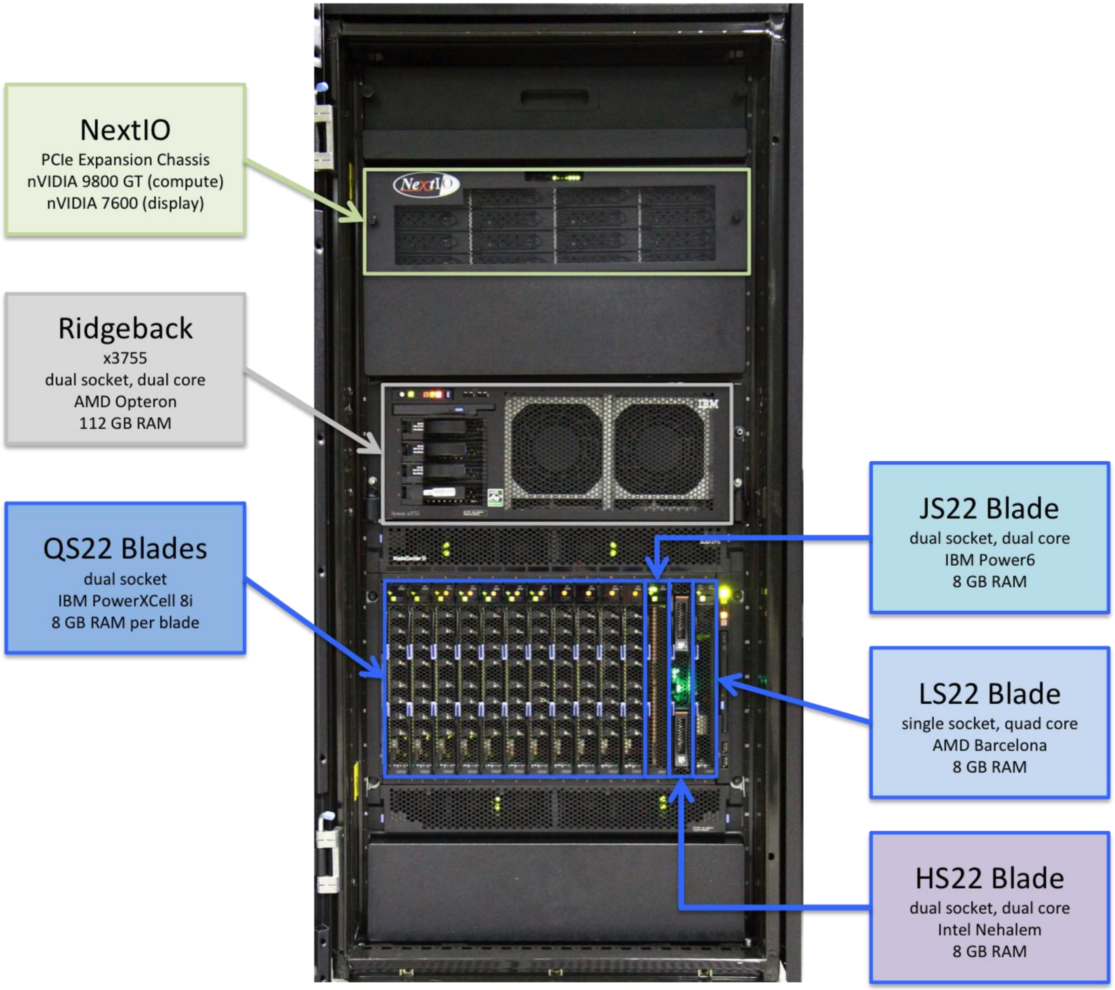
IBM Multicore (P6)



IBM Cell

nVIDIA GPU

BladeCenter H System at SC09 (contributed by IBM)



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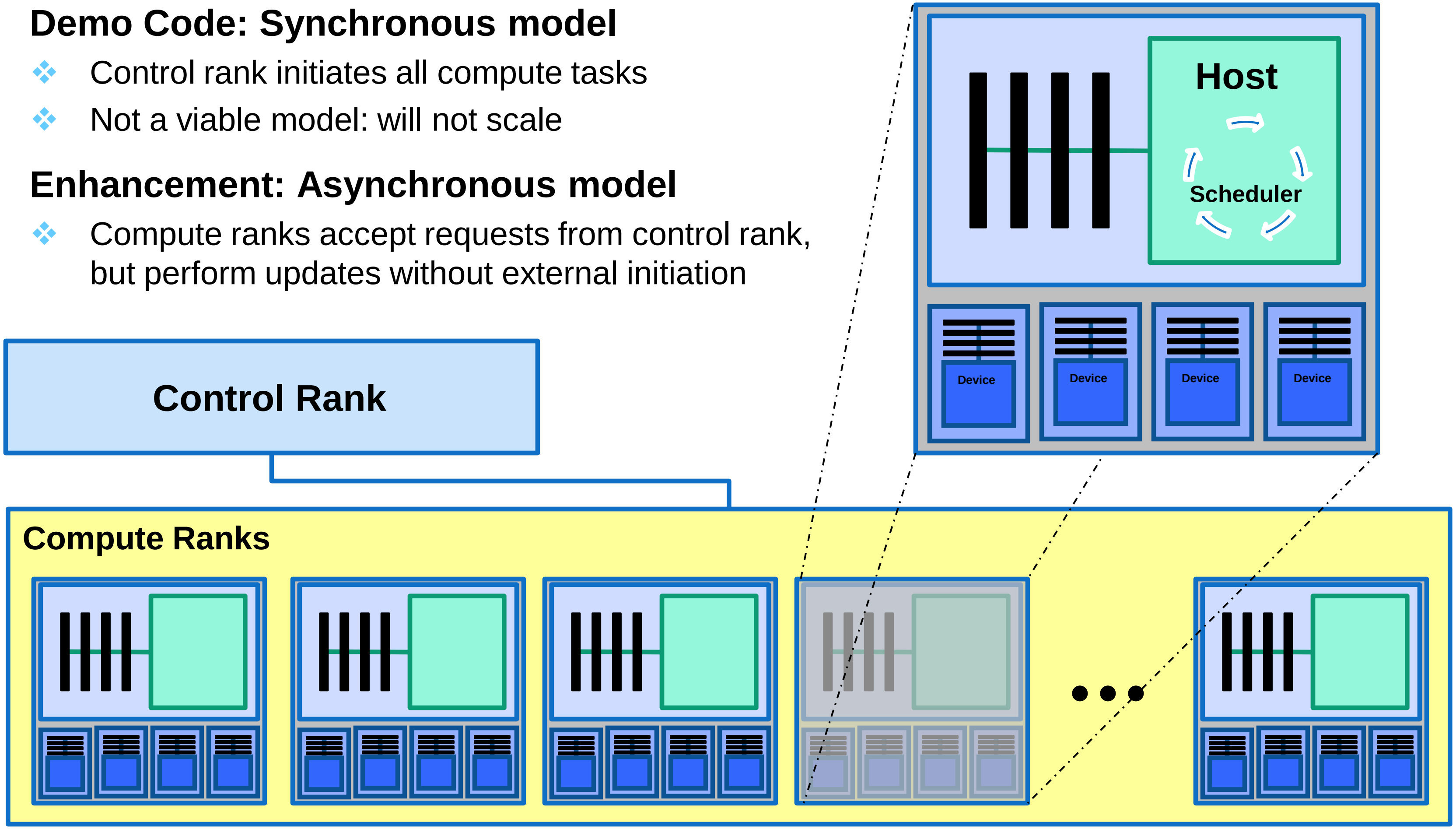
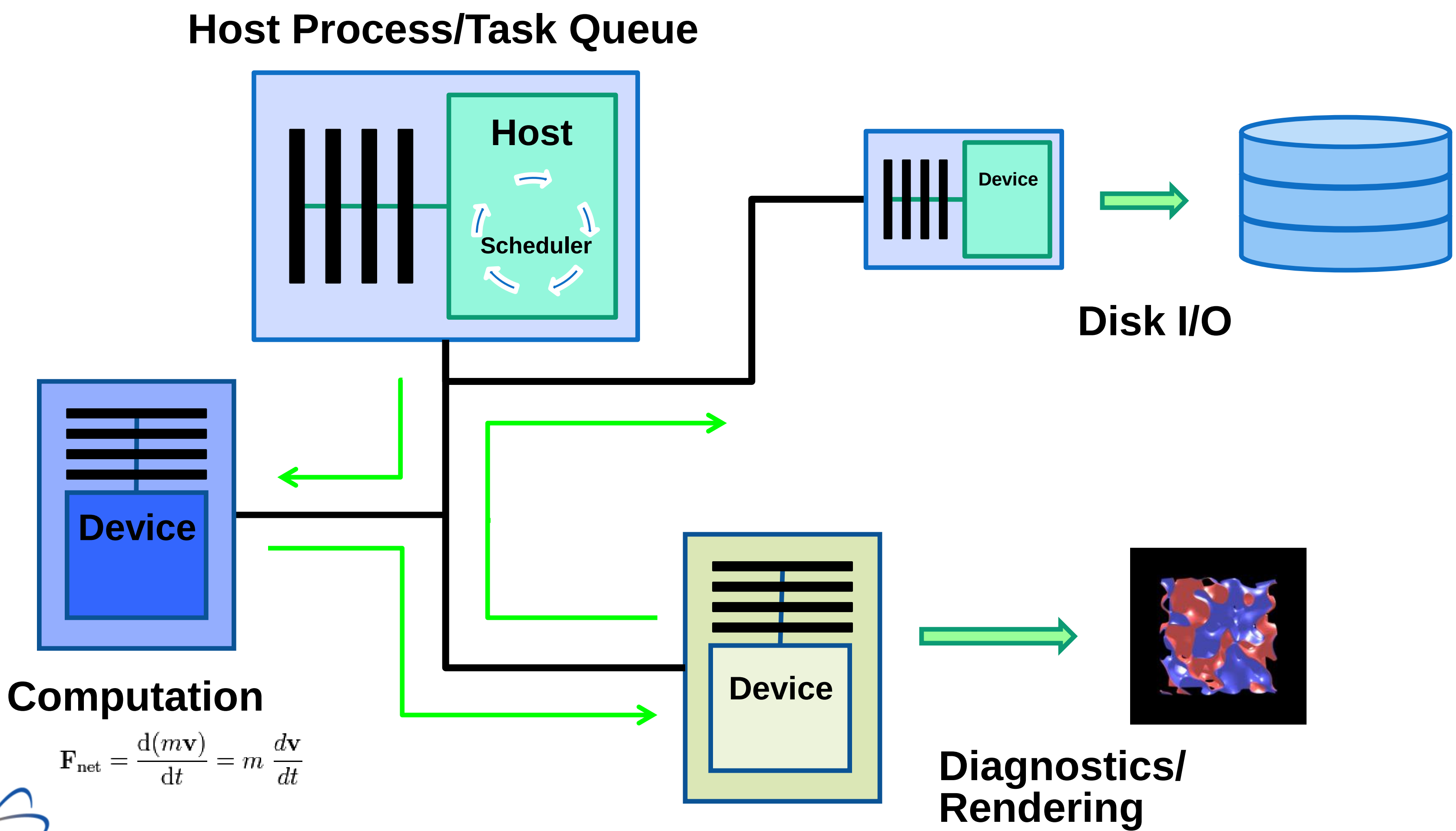
Exploiting Hybrid Architectures (Inter-Node)

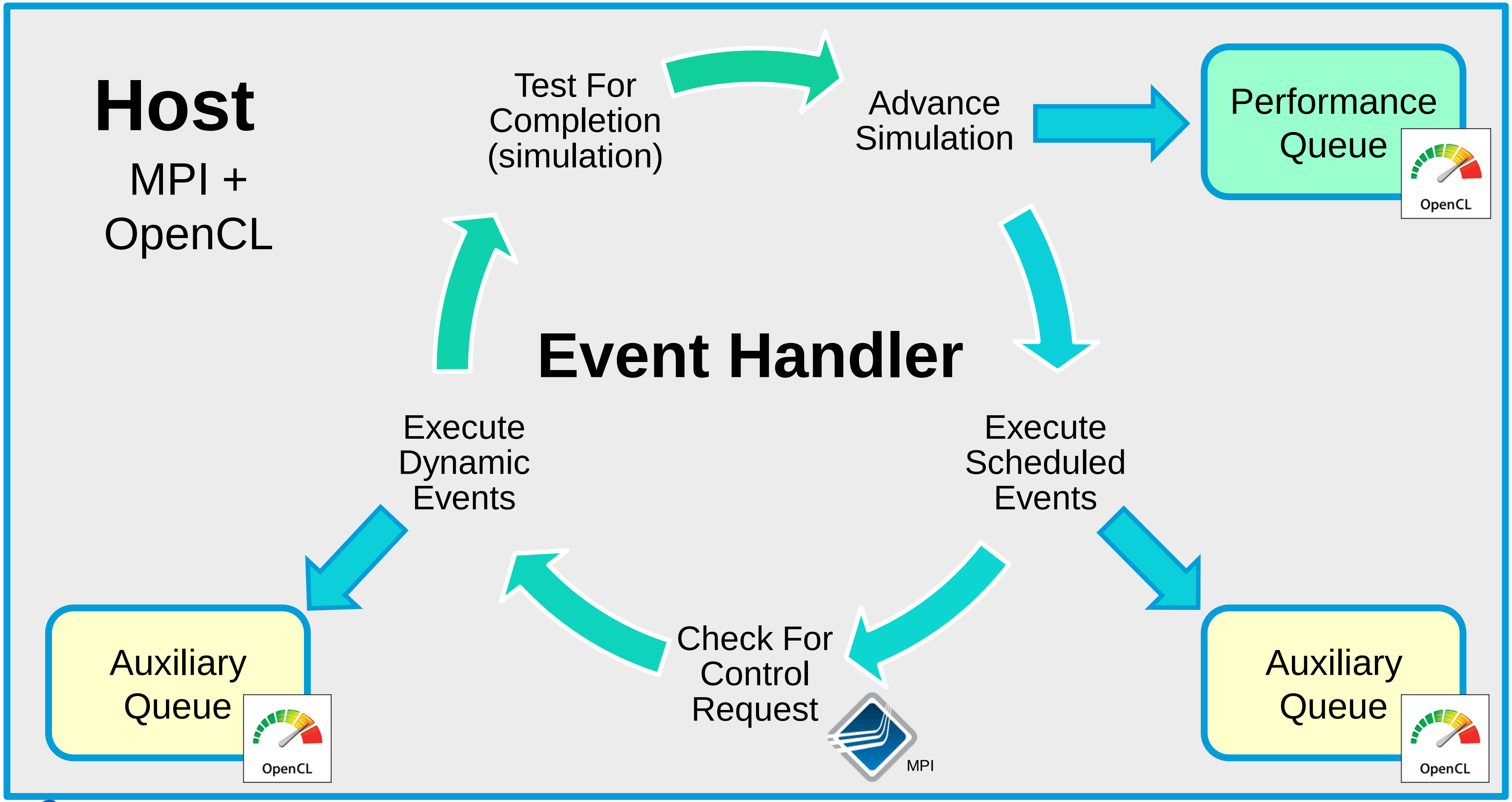
- **Demo Code: Synchronous model**
  - Control rank initiates all compute tasks
  - Not a viable model: will not scale
- **Enhancement: Asynchronous model**
  - Compute ranks accept requests from control rank, but perform updates without external initiation



Exploiting Hybrid Architectures (Intra-Node)



Compute Process Event Structure (Compute Ranks)



Functional Programming Model

- An OpenCL NDRange can be thought of as applying a functional over an index space

$$f \mapsto f(i) \;\; \forall\, i \in I$$

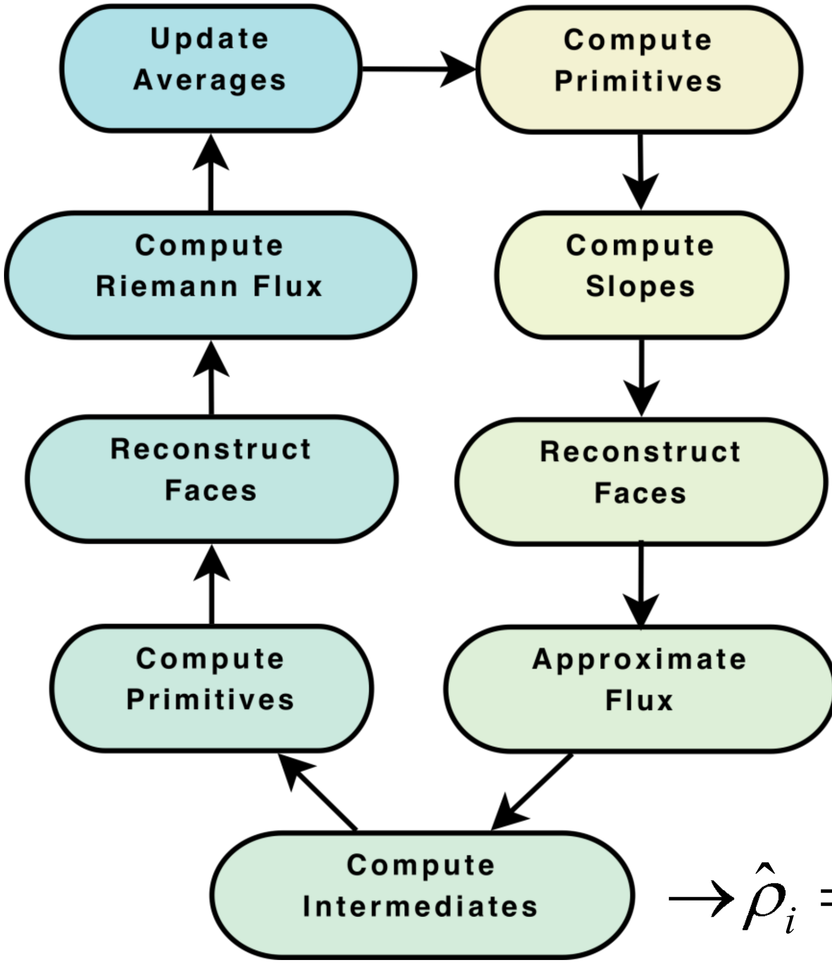
- The algorithm must be data-parallel, i.e., OpenCL functional model cannot honor lexicographical dependencies

- Standard data-parallel nested for-loop is a special case where the index is determined by a mapping from logical *N*-dimensional space to the index space

$$i \in \left(M_{\xi}(k,j) \;\forall\, k \in \left[0 \ldots N_y - 1\right], j \in \left[0 \ldots N_x - 1\right] \right)$$

```
for(k=0; k<N_y; ++k) {
  for(j=0; j<N_x; ++j) {
    c[k][j] = a[k][j] + b[k][j];
  } // for
} // for
```

Functional Expression of MUSCL-Hancock



$$\rightarrow u_i = \frac{\rho u_i}{\rho_i}$$

$$\rightarrow \sigma_i = \omega\left(q_{i+1} - q_i\right)$$

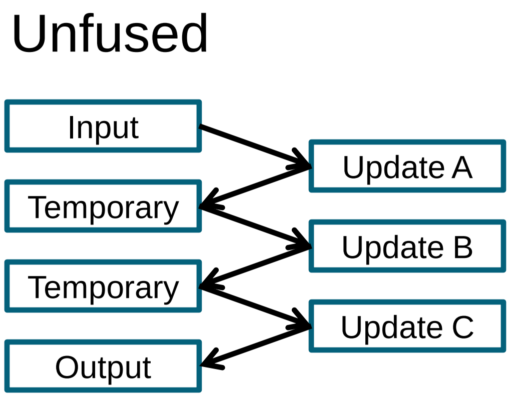
$$\rightarrow \rho_{Tail_i} = \rho_i + \frac{\Delta x}{2}\sigma_i$$

$$\rightarrow f_i^{\rho} = \rho u_{Tail_i} - \rho u_{Head_i}$$

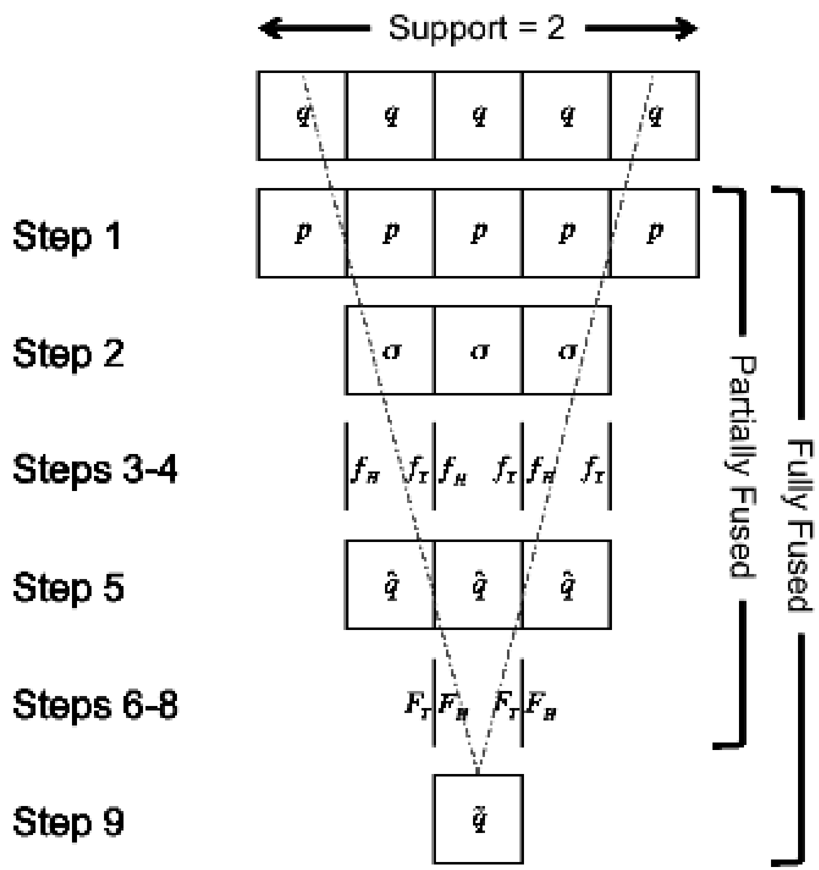
$$\rightarrow \hat{\rho}_i = \rho_i - \zeta f_i^{\rho}$$

Kernel Fusion

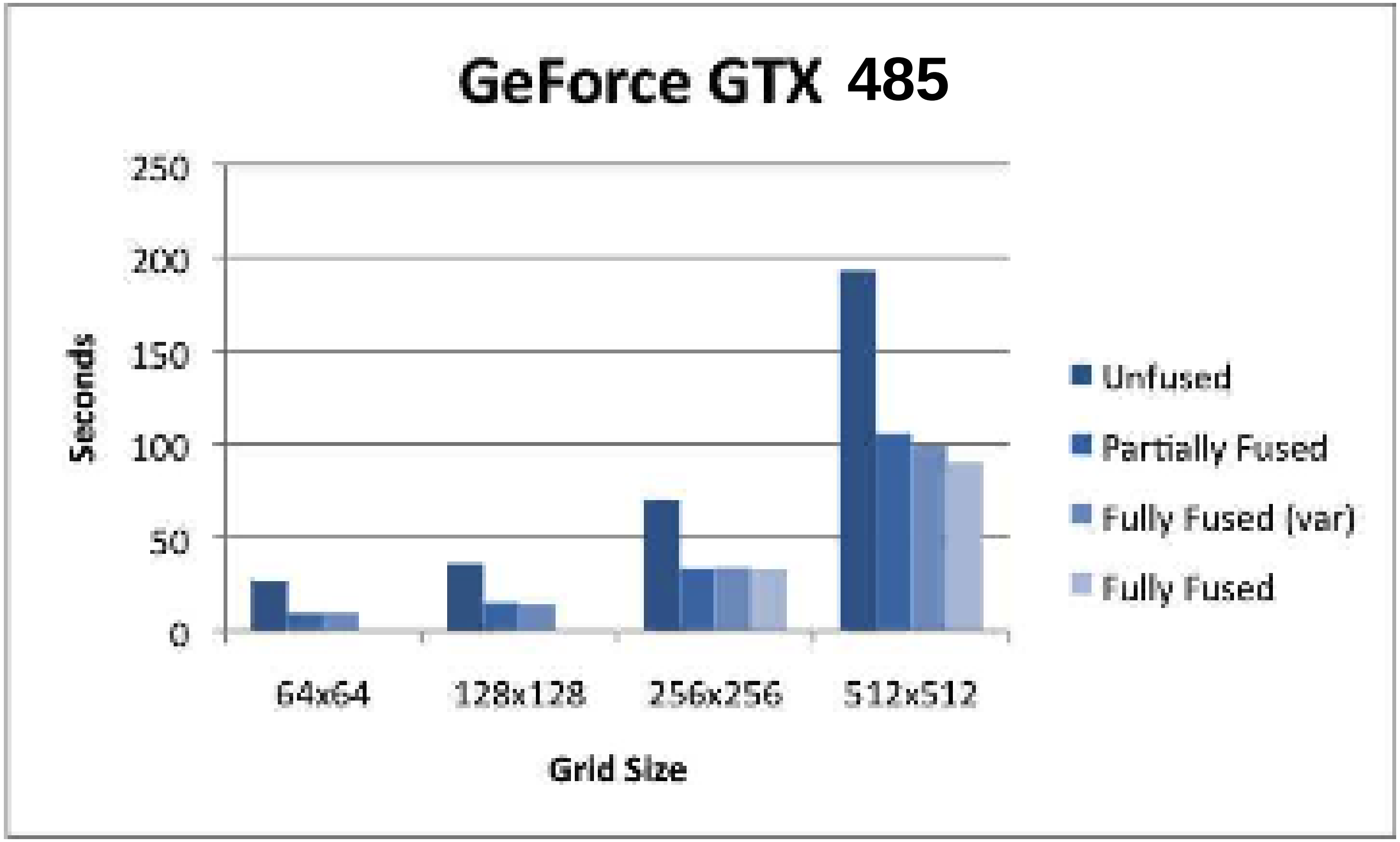
- **Original work used by-hand fusion**
  - Ugly, tedious and error-prone
  - Excellent performance increases
- **Kernel expression and optimization for functional programming**
  - GRA summer project (Ian Karlin will continue this work as a postdoc)
  - Compiler used to fuse kernels to limit data motion and increase arithmetic intensity
    - Project used POCC and Pluto to perform optimizations, e.g., array contraction



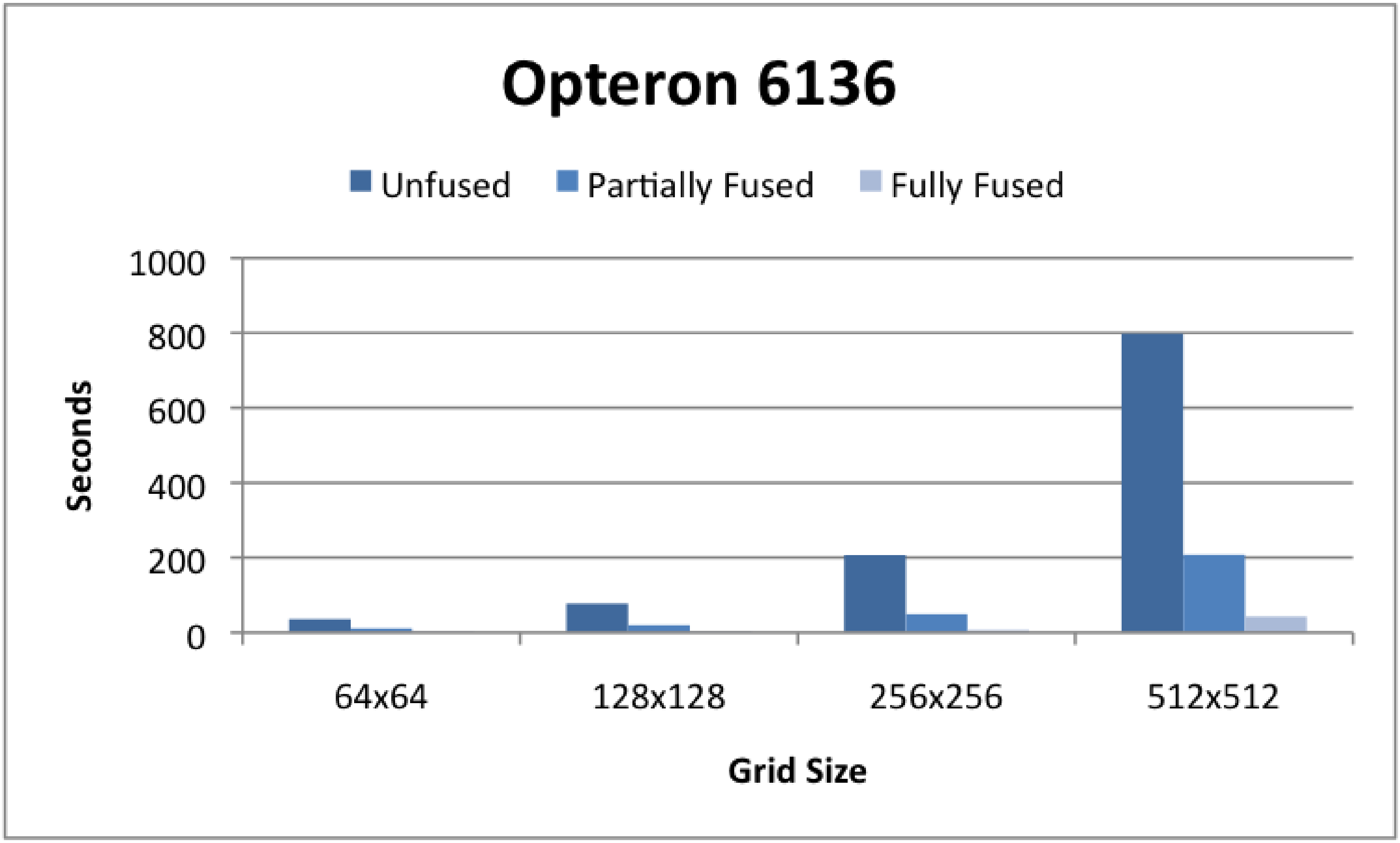
MUSCL-Hancock Numerical Support



Kernel Fusion Improvement: Fermi

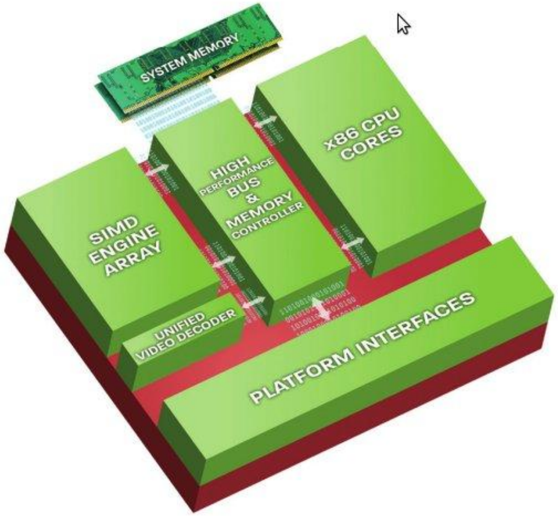


Kernel Fusion Improvement: Magny-Cours



Conclusions and Future Work

- **Hybrid Programming Model**
  - Viable start for Exascale
  - Leverages existing high-level code structure
  - Utilizes existing tools
- **Kernel Fusion**
  - Good strategy on all tested architectures
  - CPU performance is better for small problem sizes
    - Intuitive result: GPU data must traverse PCIe bus
  - Better version leaves data on the device
    - Only nearest-neighbor data moved off device



Heterogeneous designs like the IBM Cell and AMD Fusion offer the best of both worlds. Future architectures will likely converge to this paradigm.